N 62 10003

NASA TN D-1123

NASA TN D-1123

TECHNICAL NOTE

D-1123

ROCKET MEASUREMENTS OF THE UPPER IONOSPHERE BY A RADIO PROPAGATION TECHNIQUE

S. J. Bauer and J. E. Jackson

Goddard Space Flight Center
Greenbelt, Maryland

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON February 1962

D-1123

ROCKET MEASUREMENTS OF THE UPPER IONOSPHERE BY A RADIO PROPAGATION TECHNIQUE

by

S. J. Bauer and J. E. Jackson

Goddard Space Flight Center

SUMMARY

High altitude measurements of the electron density distribution have been performed well above the F2 peak of the ionosphere by using the two-frequency rocket-borne propagation experiment of Seddon. An example of a measurement of the electron density profile up to 620 km by means of the CW propagation technique is presented, including the inferred scale height and temperature of the upper ionosphere.

For the anticipated measurements up to one earth radius by the CW propagation experiment, the variation of the ionosphere below a vehicle must always be considered in order to arrive at reliable local electron density data. A correction for this time variation can be made by using recorded information on the ordinary and extraordinary propagation modes at two harmonically related frequencies. This correction procedure is briefly outlined herein.

BLANK PAGE

D-1123

CONTENTS

D-1123

ROCKET MEASUREMENTS OF THE UPPER IONOSPHERE BY A RADIO PROPAGATION TECHNIQUE*

by

S. J. Bauer and J. E. Jackson

Goddard Space Flight Center

INTRODUCTION

The rocket-borne CW propagation technique introduced by Seddon (Reference 1) for measuring ionospheric electron density is based upon the measurement of the dispersive doppler effect at two harmonically related frequencies f and $6f$. This doppler effect is produced by the motion of a rocket-borne transmitter within the ionosphere and can be expressed as a change in the phase path P of the transmitted radio wave

$$\dot{P} = \frac{2\pi f}{c}\left[n_R \dot{r} + \int_0^R \frac{dn}{dt}\, dr\right] , \tag{1}$$

where f is the transmitted frequency; c is the velocity of light in vacuo; n_R is the refractive index at the rocket, which is related to the electron density N through the Appleton-Hartree formula; and $\dot{r}$ is the velocity component of the rocket in the ray-direction. The integral term represents the time variation of the refractive index (or electron density) along the ray path. For low altitude flights and nearly vertical rocket firings, as was the case in earlier experiments, the integral term is, in general, negligibly small. However, with the extension of the CW propagation experiment to higher altitudes and more oblique propagation paths, the integral term must be considered as a correction term that is needed in order to arrive at accurate local electron densities.

EXPERIMENTAL TECHNIQUE

In the following discussion we shall consider CW propagation measurements by means of research rockets reaching altitudes well beyond the F2 peak of the ionosphere.

*Presented at the International Convention on Radio Techniques and Space Research, Oxford, England, July 5 - 9, 1961, and to be published in the J. Brit. Inst. Radio Engrs., 1962.

The following experimental arrangement was used for these measurements of the electron density distribution.

The rocket payload consists of: a transmitter delivering the two harmonically related frequencies $f = 12.267$ Mc and $6f = 73.6$ Mc, with a frequency stability of 1 part in 10^8; and a dipole antenna for each frequency. The antennas are extended telescopically to their full lengths (21 and 7 feet tip-to-tip, for f and 6f respectively) by explosive charges after nose-cone ejection.

The payload, with antennas extended, is shown in Figure 1. Prior to nose-cone ejection the antennas are folded alongside the payload frustum and therefore do not radiate

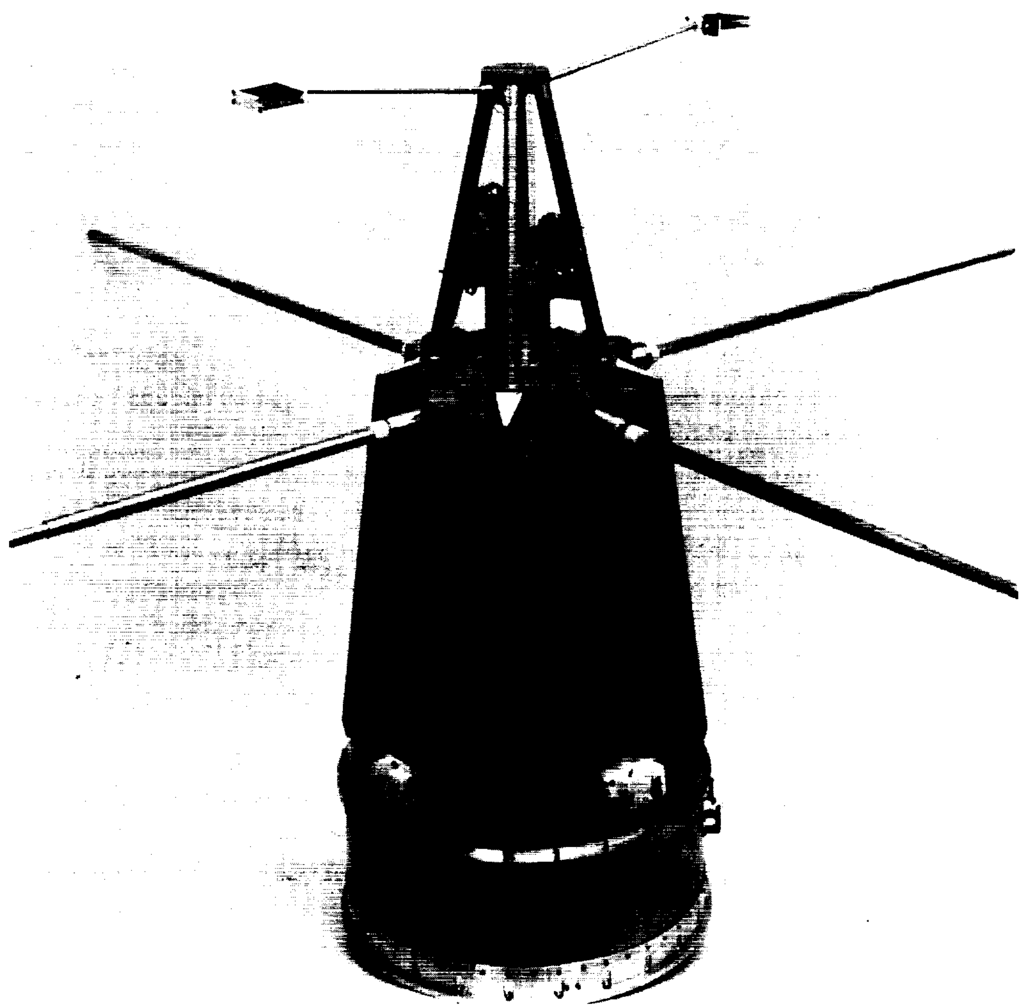

Figure 1 — ARGO D-4 rocket payload with antennas extended

D-1123

D-1123

effectively, especially at the lower frequency. For this reason actual measurements begin only after nose-cone ejection and antenna deployment.

A ground station with rather complex equipment (Figure 2), located near the launching site, receives and compares the signals transmitted by the rocket.

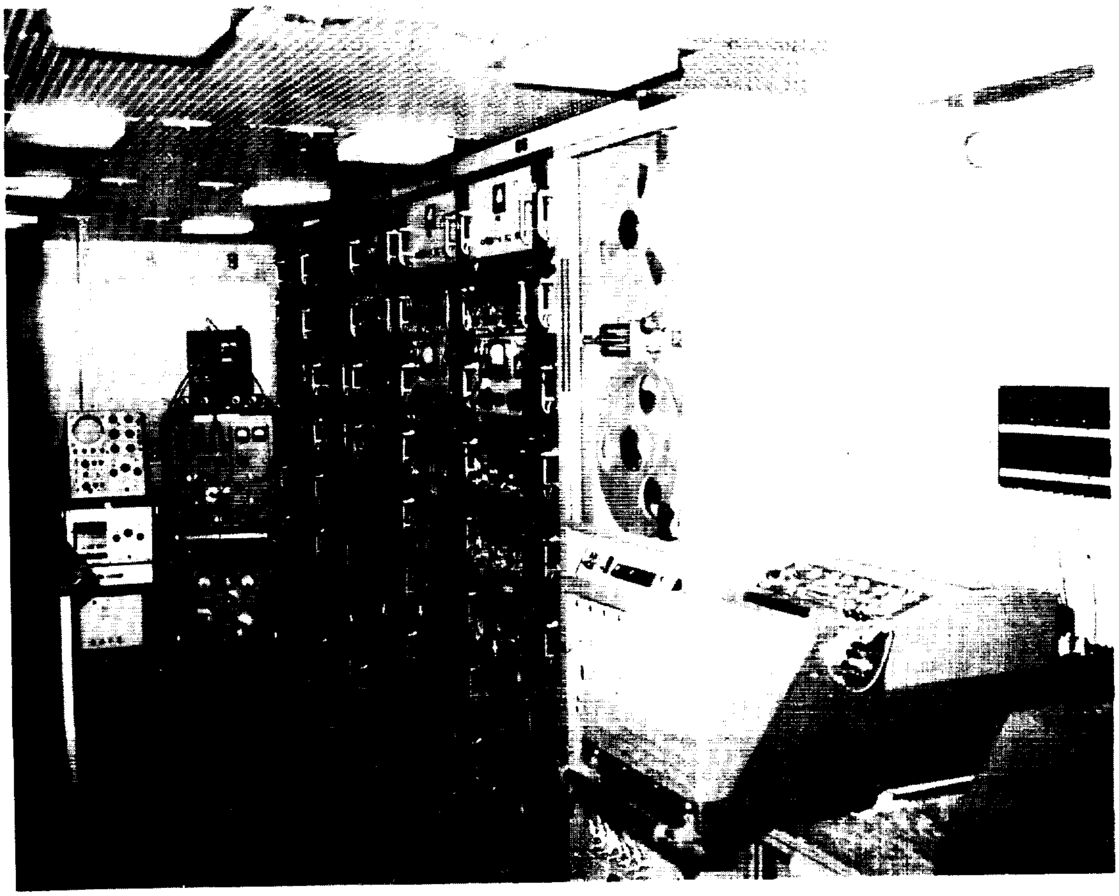

Figure 2 — Equipment at the ground station located near the launching site.

The basic quantities measured at the ground station are the beat frequencies due to the difference between the received high and low frequencies $6f$ and f. The low frequency is multiplied by the harmonic factor $(m = 6)$ at the ground for both magneto-ionic components, which are separated by virtue of their polarization using proper antenna arrangements.

The beat frequencies obtained by the ground station equipment can be expressed by

$$(FB)_{o,x} = \frac{6f}{c}\left[\left(n^{(h)}_{o,x} - n^{(\ell)}_{o,x}\right)\dot{r} + \int_0^R \frac{d}{dt}\left(n^{(h)}_{o,x} - n^{(\ell)}_{o,x}\right) dr\right] \pm \text{roll correction,} \qquad (2)$$

where $n^{(h)}$ is the refractive index at the high frequency $6f$, $n^{(\ell)}$ is the index at the low frequency f and the subscripts $_o$ and $_x$ refer to the ordinary and extraordinary components, respectively.

The first term of Equation 2 is related to the electron density at the rocket, while the second term represents a correction due to the time variation of the electron density distribution along the ray path. The ordinary and extraordinary beat frequencies, as well as their algebraic combinations, are directly available from the ground station.

EXPERIMENTAL RESULTS

For a recent experiment which we shall discuss here as an example, the analysis was based upon the sum of the ordinary and extraordinary beat frequencies which may be expressed, to a first approximation, as

$$F_S = \frac{6f}{c}\left[\left(n^{(h)}_o + n^{(h)}_x\right) - \left(n^{(\ell)}_o + n^{(\ell)}_x\right)\right]\dot{r} \, . \qquad (3)$$

The sum F_S has the advantage of being free of roll effects, since the individual ordinary and extraordinary beat frequencies have equal but opposite roll corrections. Furthermore, F_S is almost independent of the earth's magnetic field over the altitude and electron density range covered by this particular experiment. However, the consistency of the data obtained can be checked by analyzing the individual ordinary or extraordinary beat frequencies. The roll rate of the rocket needed for correcting the individual beat frequencies is also obtained at the ground station from the received high frequency signal, after a slight correction for the Faraday rotation at this frequency.

From F_S an apparent local electron density, corresponding to

$$N' = \frac{1}{\Delta r}\left(\int_0^{P_2} N\, dr - \int_0^{P_1} N\, dr\right) \, , \qquad (4)$$

D-1123

can be obtained by means of the Appleton-Hartree formula together with trajectory information giving the radial velocity component of the rocket.

The electron densities obtained in this manner are not true local electron densities because the integral term (see Equation 2) was neglected in the expression for F_S (Equation 3). For a quiet ionosphere, that is, no rapid changes in the electron density distribution along the ray path and an absence of significant horizontal gradients, the integral term is due mainly to the geometry of the trajectory. For a spherically stratified ionosphere, the true electron density can be derived from the apparent electron density on the basis of the following correction procedure which follows from simple geometrical considerations (Figure 3):

$$N = N' + \frac{\epsilon}{1-\epsilon}\left(N' - \bar{N}\right) \qquad (5)$$

in which

$$\epsilon = \frac{\dot{\theta}\, r \tan\theta_r}{\dot{r}},$$

where θ is the zenith angle of the position vector at the ground station and θ_r is the zenith angle of the position vector at the rocket, r is the radial distance between ground station and rocket as defined by Figure 3,

and $\bar{N} = \frac{1}{r}\int_0^r N\, dr \cong \frac{1}{r}\int_0^r N'\, dr.$

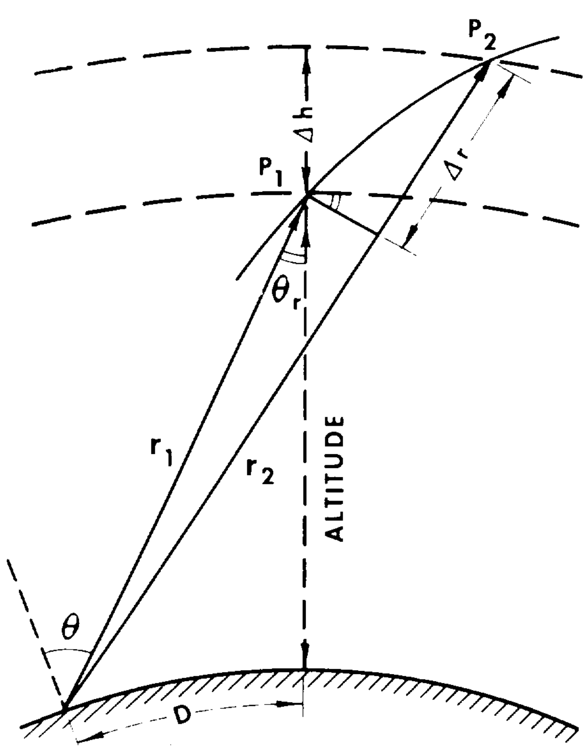

Figure 3 - Geometry for the obliquity correction

The results of the electron density measurements from a recent 4-stage research rocket of the type ARGO D-4 are shown in Figure 4. The dashed line represents the apparent (uncorrected) electron density profile obtained from the sum F_S (Equation 3), while the solid line represents the electron density profile after applying the obliquity correction outlined above (Equation 5). For this particular case the simplified correction

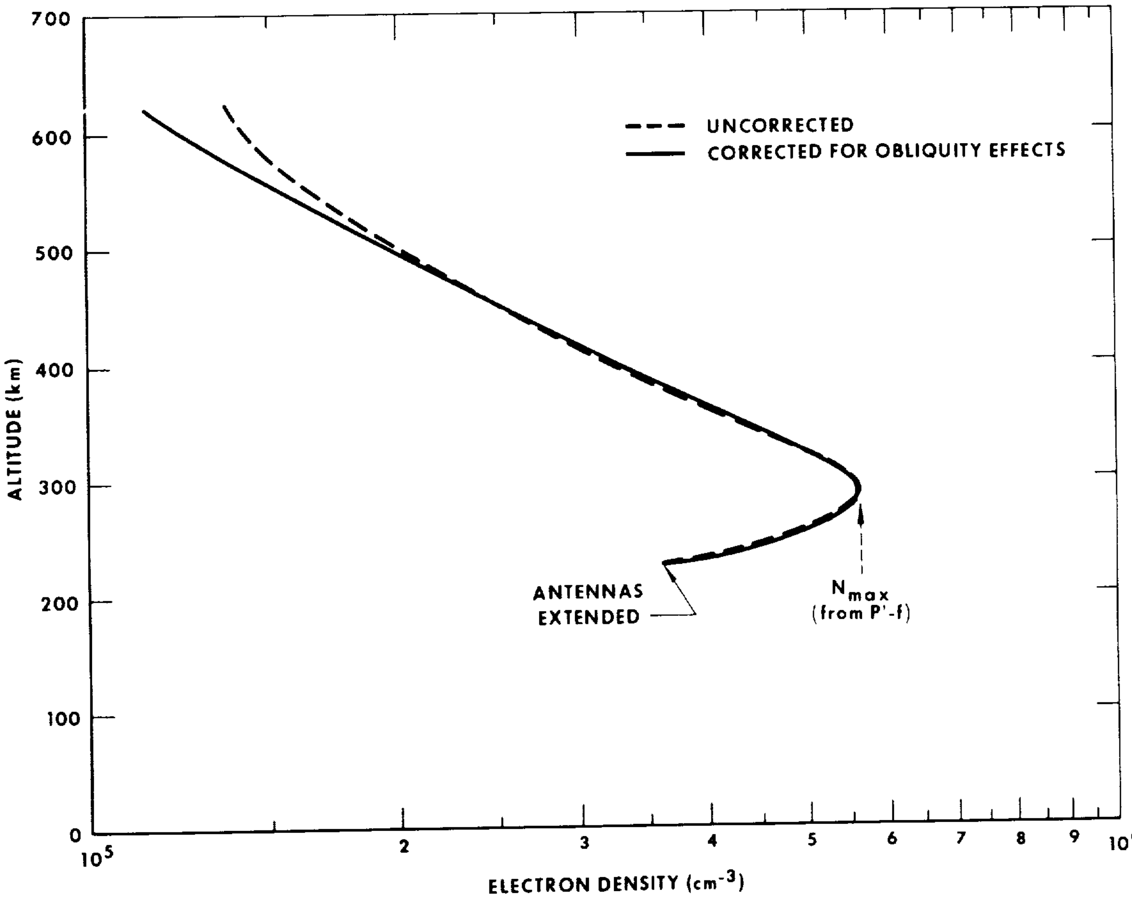

Figure 4 – Electron density measurements from a 4-stage research rocket of the type ARGO D-4 fired from Wallops Island, Virginia, 1502 EST, April 27, 1961

procedure was applicable because the ionosphere was very quiet during the firing and no horizontal gradients were indicated from the vertical incidence soundings of the ionosphere at three neighboring stations.

Although the obliquity correction at 620 km is only of the order of 20 percent, the importance of this correction becomes apparent when we attempt to interpret the physical significance of an electron density profile. On the basis of the uncorrected profile we could deduce a positive scale height gradient with the implication of increasing temperature in the region above the F2 peak. The actual profile based on the corrected electron density, however, represents a diffusive equilibrium distribution in an isothermal upper ionosphere.

It should be noted that a number of the published electron density profiles above the F2 peak, obtained from rocket measurements using propagation techniques, resemble our uncorrected profile. This suggests that the correction outlined here may not have been made and that caution should be exercised in the geophysical interpretation of such profiles.

From the practically constant logarithmic slope of our electron density distribution above the F2 peak (Figure 4), a scale height for the electron-ion gas of the order $H' \approx$ 200 km is obtained. Assuming that local thermodynamic equilibrium exists and that the major ionic constituent is atomic oxygen, this scale height corresponds to a temperature $T \approx 1640°K$ for the altitude region from 350 to 620 km – in good agreement with daytime temperatures derived from satellite density data (Reference 2).

D-1123

CW PROPAGATION TECHNIQUE FOR HIGH ALTITUDE ROCKETS

While the simplified correction procedure is applicable for a quiet ionosphere, this is not the case when the ionospheric electron density distribution varies rapidly with time, e.g., at sunrise or during ionospheric disturbances. Moreover, in the case of altitudes well above 1000 km the integral term in Equation 2 can assume major importance even for almost vertical firing, since the contribution of the time-varying integral term may become comparable in magnitude to the term representing the local electron density.

In principle, the integral term can be eliminated if simultaneous Faraday-rotation and Doppler measurements are being made, as was first suggested by Kelso (Reference 3). For high frequencies this procedure is relatively straightforward. For frequencies as low as 12.267 Mc, which provide a more sensitive measure of the ionospheric electron density, a simple approximation to the Appleton-Hartree formula is not sufficient for an accurate determination of the local electron density. However, with all the quantities measured in the CW propagation experiment it is possible to arrive at a solution for the local electron density at the rocket, based on the complete Appleton-Hartree formula, taking into account the effect of a time-varying electron density distribution along the ray path.

The sum (Σ) and difference (Δ) of the ordinary and extraordinary beat frequencies, as defined by Equation 2, are given by

$$\Sigma = \frac{mf}{c} \left[N_1 \dot{r} + \int_0^R \frac{dN_1}{dt} \, dr \right] , \tag{6}$$

$$\Delta = \frac{mf}{c}\left[N_2\,\dot{r} + \int_0^R \frac{dN_2}{dt}\,dr\right], \tag{7}$$

where

$$N_1 = \left(n_o^{(h)} + n_x^{(h)}\right) - \left(n_o^{(\ell)} + n_x^{(\ell)}\right)$$

and

$$N_2 = \left(n_o^{(\ell)} - n_x^{(\ell)}\right) - \left(n_o^{(h)} - n_x^{(h)}\right).$$

The quantities N_1 and N_2 are expressed in terms of the refractive indices given by the complete Appleton-Hartree formula. It is convenient to represent N_1 and N_2 graphically as a family of curves.

Setting $N_1 = \lambda N_2$, where $\lambda(N,\vec{H})$ is a parameter which depends upon the electron density N and the earth's magnetic field $\vec{H}$, we can write

$$\lambda\,N_2\,\dot{r} + \bar{\lambda}\int_0^R \frac{dN_2}{dt}\,dr = \frac{c}{mf}\,\Sigma\,, \tag{8}$$

$$N_2\,\dot{r} + \int_0^R \frac{dN_2}{dt}\,dr = \frac{c}{mf}\,\Delta\,, \tag{9}$$

where

D-1123

$$\overline{\lambda} = \frac{\int_0^R N_1 dr}{\int_0^R N_2 dr} .$$

Both $\int_0^R N_1 dr$ and $\int_0^R N_2 dr$ can be computed by numerical integration from the complete Appleton-Hartree formula on the basis of the measured electron density profile, uncorrected for the time variation along the ray path.

The simultaneous solution of Equations 8 and 9 yields

$$N_2 = \frac{c}{mf}\left[\frac{\Sigma - \overline{\lambda}\Delta}{(\lambda - \overline{\lambda})\dot{r}}\right] . \tag{10}$$

The local electron density at the rocket can now be determined from N_2 by means of the complete Appleton-Hartree formula.

It should be noted that the general correction outlined above includes the time variation of the electron density distribution along the ray path due to the geometry of the trajectory as well as the explicit time variation of the ionosphere. Although the general correction could, in principle, be applied to rocket flights below 1000 km, such as the one illustrated earlier, the procedure is more complicated because of the additional evaluation of the beat-frequency difference Δ, as well as the roll correction. Furthermore, for a quiet ionosphere it does not improve the accuracy of the local electron density above that obtained by means of the relatively simple obliquity correction.

The previous discussion was based on rather idealized conditions. However, with research rockets, near-vertical firings with zenith angles of 4 to 10 degrees can be realized. Thus, problems like refraction or path-splitting of the ordinary and extraordinary propagation modes do not become as serious as they do in satellite propagation work — at least not on the upward leg of the trajectory which is mainly used for the CW propagation experiment. If the need arises, the more complicated situation can be considered by ray tracing procedures with electronic computers, as has been shown for satellite propagation studies (Reference 4). A detailed theoretical discussion of propagation phenomena in a time-varying inhomogenous ionosphere, applicable to rocket and satellite measurements, has recently been given by Kelso (Reference 5).

The upper limit for the propagation experiment is mainly determined by the magnitude of the beat frequency and the applicability of the correction procedure. Theoretically derived beat frequencies based on estimates of ionospheric structure and vehicle performance for the ARGO D-4 and Scout vehicles are shown in Figure 5. It can be seen that for the Scout the beat frequency drops to 1 cps about 800 seconds after take-off (an altitude of about 4000 km). However, it is possible to average the readings of beat frequency over longer time intervals, and thus it appears feasible to make useful measurements at even greater altitudes. The time period over which the beat notes are read may be of the order of several seconds. Thus, the height interval is small as compared to the local scale height (which is of the order of a few hundred kilometers owing to the predominence of light ionic constituents above 1500 km).

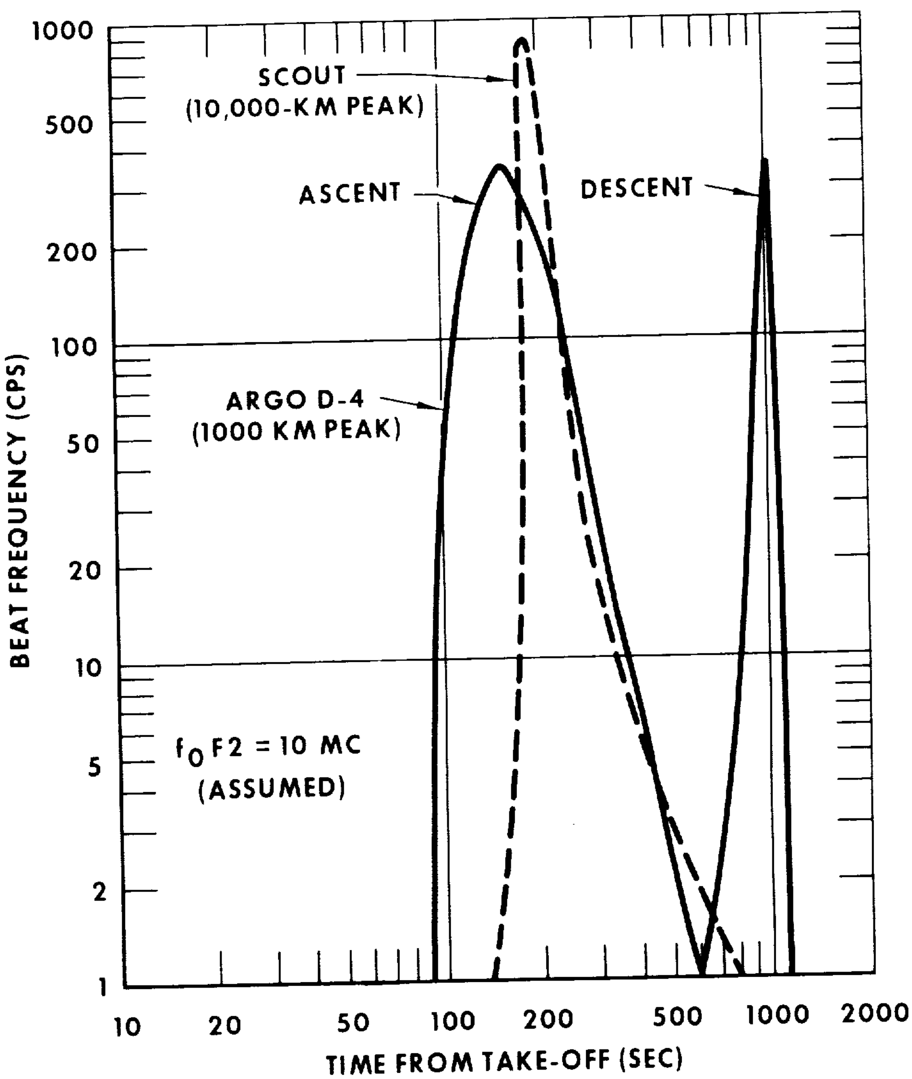

Figure 5 — Theoretically derived beat frequencies versus time, based on estimates of ionospheric structure and vehicle performance for the ARGO-4 and SCOUT vehicles

The Scout vehicle should make it possible to measure with good accuracy the electron density distribution in the upper portion of the ionosphere, and with reasonable accuracy the electron densities within the protonosphere.

Measurements of the electron density distribution well above the F2 peak of the ionosphere should also permit the determination of other structural parameters of the upper atmosphere, such as temperature and the concentration of light ions (Reference 6). To make full use of the rocket vehicle, a direct-measurement technique such as an RF-impedance probe is included in the payload. The RF probe measures electron density on the downward leg of the flight where the propagation experiment is handicapped by the oblique propagation paths. The propagation experiment also provides in-flight calibration on the upward leg for the direct measuring technique, since the RF-probe has not yet achieved the degree of measurment accuracy (±2 percent) which can be realized with the propagation technique under undisturbed conditions.

The CW propagation technique, which has in the past proven itself a useful tool for ionospheric research, may also find application in the future exploration of planetary ionospheres.

ACKNOWLEDGMENTS

The instrumentation for the CW propagation experiment was designed by G.H. Spaid and J. R. Hagemeyer. The contributions of J. C. Seddon to the design of the system are gratefully acknowledged.

REFERENCES

1. Seddon, J. C., "Propagation Measurements in the Ionosphere with the Aid of Rockets," J. Geophys. Res. 58(3):323-335, September 1953

2. Jackson, J. E., and Bauer, S. J., "Rocket Measurement of a Daytime Electron Density Profile up to 620 KM," to be published in J. Geophys. Res., 1961; also NASA Technical Note D-413, September 1961

3. Kelso, J. M., "The Measurement of Electron Densities in the Outer Ionosphere," Electromagnetic Wave Propagation: Proceedings of a Conference Sponsored by the Postal and Telecommunications Group of the Brussels Universal Exhibition, Ed. by M. Desirant and J. L. Michiels, London and New York: Academic Press, 1960, pp. 291-298

4. Little, C. G., and Lawrence, R. S., "The Use of Polarization Fading of Satellite Signals to Study the Electron Content and Irregularities in the Ionosphere," J. of Res. of

the U. S. Natl. Bur. of Standards, Section D, Radio Propagation 64D(4):335-346, July-August 1960

5. Kelso, J. M., "Doppler Shifts and Faraday Rotation of Radio Signals in a Time-Varying, Inhomogeneous Ionosphere, Part II," J. Geophys. Res. 66(4):1107-1115, April 1961

6. Bauer, S. J., "The Electron Density Distribution and Associated Atmospheric Parameters above the F2 Peak," NASA Technical Note D-1171, in press, and Journal of Atmospheric Sciences (formerly Journal of Meteorology), 1(1), January 1962, to be published .

D-1123